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| 6. AUTHOR(S)<br><br>C. Randall Truman and Rick I. Zadoks  |  |   |                                  |  |  |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><br>Department of Mechanical Engineering<br>University of New Mexico<br>Albuquerque, NM 87131   |  |   |                                  | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER                                    |  |
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| 13. ABSTRACT (Maximum 200 words)<br>The importance of large-scale (or coherent) structure to optical propagation through turbulent shear flow has been demonstrated. Direct simulations of low-Reynolds-number flows which include a passive scalar as well as experimental data have been examined. A passive scalar in the simulations is related to refractive-index fluctuations, while a heated jet was used in the experiment. Large fluctuations associated with large-scale turbulent structure produce a majority of the optical phase error. A low-order dynamical model for the near-wall region of a turbulent channel flow was developed. These predictions illustrate the importance of the dynamics of the turbulent shear flow to optical phase error. Techniques to use limited data to estimate the effect of large-scale structure upon optical propagation were developed.<br>A round turbulent jet was also studied using a large eddy simulation as well as experimental data. Temperature at several locations and jitter in an optical beam propagated through the flow can be measured simultaneously in an experimental facility constructed at the Air Force Phillips Laboratory. A low-dimensional dynamical model for the round jet with passive scalar to be developed in subsequent work will be compared with this experimental data. |  |   |                                  |  |  |
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# **DYNAMICAL SYSTEM PREDICTION OF THE SCALAR FIELD IN A TURBULENT CHANNEL FLOW**

C. Randall Truman and Rick I. Zadoks  
Department of Mechanical Engineering  
University of New Mexico  
Albuquerque, NM 87131

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Final Technical Report for Period 01 November 1990 - 31 January 1994

Prepared for

**Dr. James M. McMichael, Program Manager**  
**AIR FORCE OFFICE OF SCIENTIFIC RESEARCH**  
110 Duncan Avenue Suite B115  
Bolling AFB, DC 20332-0001

## **RESEARCH OBJECTIVES**

Developing a computational model for the scalar fluctuations in the near-wall layer of a turbulent channel flow was the primary objective of this research. These scalar fluctuations represent the instantaneous index-of-refraction field that is needed to predict the optical degradation experienced by a coherent beam passing through the shear flow. In practice, density fluctuations resulting from variations in temperature or species concentration produce the index-of-refraction fluctuations.

A deterministic model is required to predict the intermittent and anisotropic nature of the vortical and scalar fields. An existing finite-dimensional dynamical system model for the near-wall region of a turbulent flow was employed to predict the velocity field. The corresponding passive-scalar distribution was computed from a transport equation developed from first principles. The predicted scalar fields were compared with those produced by direct numerical simulations and observed in experiments to determine the feasibility of using a low-order dynamical system to predict the qualitative features of the observed scalar field.

A secondary objective was to examine the relative influence of the turbulent scales of the vortical and scalar fields upon optical propagation. Dominance of large scale structures would support using a low-dimensional dynamic model for the scalar field to study the effects of turbulent flow dynamics on optical phase error. This deterministic model of the scalar field is inexpensive to compute and the data sets are of manageable size.

A third objective, added for the third year of the grant, was to develop an experimental facility at the Air Force Phillips Laboratory to study aero-optic effects in free shear flows. The dynamics of flow variables, such as temperature and velocity, will be measured simultaneously with optical effects. Beam jitter, that is the motion of a laser beam projected through the flow, will be used to study the dynamics of a heated, round turbulent jet.

## **STATUS OF RESEARCH**

These objectives of the research were completed during the grant period:

1. investigate the direct simulation database for the turbulent channel flow using several time realizations of velocity and scalar fields acquired from the Center for Turbulence Research (CTR) at the NASA-Ames Research Center;
2. construct the dynamical model for velocity in the near-wall region of a turbulent flow based on computational eigenmodes;
3. develop a low-dimensional dynamical model for the scalar field in the near-wall region of the turbulent channel flow and explore its behavior over a range of parameters;
4. compare the predicted scalar fields and resulting phase error distributions with those from the original direct simulation database;
5. develop an experimental facility at the Air Force Phillips Laboratory in which flow and optical parameters can be measured simultaneously.

### Relative influence of turbulent scales

Recent studies of optical propagation through turbulent shear layers (Truman & Lee, 1990; Chew & Christiansen, 1991; Wissler & Roshko, 1992; Jumper & Hugo, 1992; Truman, 1992) have shown that the effect of turbulent fluctuations upon optical quality cannot be adequately modeled by assuming isotropic, homogeneous turbulence. Phase distortion introduced by refractive-index fluctuations is highly anisotropic since the distribution of these fluctuations is strongly influenced by the large-scale vortical structure in the flow. The magnitude as well as the distribution of optical distortion are dependent on the direction of propagation of the optical beam with respect to the orientation of the large-scale structure (Truman & Lee, 1990). The phase error distribution is produced by regions of large scalar fluctuations which are elongated in the streamwise direction corresponding to the large-scale vortical structure.

The relative contributions of the large-scale and small-scale structure in the vorticity and scalar fields to optical phase error were examined. Large fluctuations in the scalar field which induce the majority of the phase error correlate with large velocity fluctuations typical of the large-scale vortical structures. Figure 1 shows the joint probability density function (PDF) for streamwise velocity and scalar fluctuations from the direct numerical simulation (DNS) of a homogeneous shear flow of Rogers et al. (1986). The mean gradient of the passive scalar  $\theta$  is normal to the mean flow direction with the same sign as the streamwise velocity gradient.

Figure 2 represents the integrand of the correlation coefficient  $\overline{u\theta}$ , which is about  $0.65u_{rms}\theta_{rms}$  for the homogeneous shear flow. It is clear that large fluctuations (arbitrarily defined as larger than one rms) contribute most heavily to the high correlation between streamwise velocity and scalar fluctuations. Figure 3 is the same quantity for the DNS of a turbulent channel flow by Kim (1988) for a plane at  $y^+ = x_2^+ = 16$ , where turbulent production is largest. The strong correlation between velocity and scalar fluctuations in the near-wall region has been observed in the direct simulation data by Guezennec et al. (1990), in experiments by Antonia et al. (1988) and in large eddy simulations by Horiuti (1988). This correlation is a result of motions caused by large-scale vortical structure. Motions outward from the (hot) wall cause negative velocity fluctuations and positive scalar fluctuations, while motions toward the wall produce fluctuations with opposite signs. Once again, large fluctuations in streamwise velocity and scalar are seen to be highly correlated. This is significant for optical propagation in which the phase error induced by turbulence is directly proportional to the refractive-index (or scalar) fluctuations along the direction of propagation. Large scalar fluctuations which are highly correlated with large streamwise velocity fluctuations produced by the large-scale vortical structure contribute most significantly to phase error during propagation through a shear layer. The relationship between the vortical structure and the scalar field in the homogeneous shear flow is discussed by Truman & Lee (1990).

The dominance of large fluctuations in producing phase error for the near-wall region of the channel flow ( $y^+ = x_2^+ \leq 40$ ) is also illustrated by Figure 4 in which the contribution to phase error (proportional to scalar fluctuation) by fluctuations smaller than a given value is plotted against the volume occupied by these fluctuations. Fluctuations larger than one rms

occupy just 30% of the volume yet contribute more than 60% of the phase error. The phase error which resulted from propagating through this scalar field with all fluctuations smaller than one rms removed was found to be quite similar to the phase error using the full scalar field (Truman, 1992).

#### Dynamical model for a passive scalar

These results suggest that a prediction of a turbulent shear layer which resolves the large-scale vortical structure can adequately describe the scalar field and the resulting optical degradation. Thus a model was developed to predict the large-scale scalar structure in a near-wall turbulent flow following a dynamical system approach. Optical phase distortion produced by such a scalar field was examined and compared with that caused by the original DNS scalar field. The velocity field for the direct numerical simulation (DNS) of turbulent channel flow by Kim et al. (1987) and Kim (1988) has been decomposed into optimal eigenmodes through a proper orthogonal decomposition by Moin & Moser (1989). These eigenmodes for the near-wall region were used to derive a 10-mode nonlinear dynamical model (DM) similar to that used by Aubry et al. (1988).

For a passive scalar, a "conservation of scalar" equation has nearly the same form as a momentum balance equation. Since the scalar is passive, it has no influence on the momentum balance; the velocity equations are solved independently. Thus the resulting scalar transport equation is linear in scalar fluctuations, with convective velocities obtained from the velocity DM. Rather than performing a proper orthogonal decomposition (POD) of the scalar field, the high correlation between the streamwise velocity and scalar fields was exploited. The basis for the scalar model was taken to be the POD eigenmodes for the streamwise velocity. Similar to the velocity DM, the first normal eigenmode and five (complex) spanwise Fourier modes were used, leading to a system of ten ODEs in time; streamwise variations are neglected in this simple model. A Heisenberg model for the effect of scales smaller than those resolved with the POD modes was employed, similar to Aubry et al. (1988). Diffusion of the scalar required the inclusion of a turbulent Prandtl number (of order one). Additional details are available in Larson et al. (1993).

Decreasing the Heisenberg parameter, which reduces the dissipation of energy by scales smaller than those resolved by the DM, produced the expected dynamical behavior, changing from periodic (or semi-periodic), to intermittent and finally to chaotic. Following Aubry et al. (1988), the intermittent solution was selected as most representative of the actual burst-and-sweep dynamics of the near-wall region. Figure 5 shows a time history for the scalar at one location in the flow. The dynamical behavior was seen to oscillate about two fixed points, each representing pairs of counter-rotating streamwise vortices, as shown by the contour plots of scalar fluctuation fields at  $t^+ = 18000$  and  $t^+ = 36000$  included in Figure 6.

Comparisons with the original DNS data for mean and rms fluctuation quantities were made, where streamwise distance in the DNS is related to time in the DM. Figure 7 shows the normal distribution of rms fluctuations in the streamwise and normal velocity components. Although the normal velocity component is underpredicted, the Reynolds stress distribution shown in Figure 8 is quite good. This is believed to indicate that the high correlation between streamwise and normal components of velocity fluctuations is preserved in the POD

eigenmodes. The rms scalar distribution across the shear layer is shown in Figure 9 with a turbulent Prandtl number equal to 1. The DM underpredicts the scalar fluctuations, especially in the outer part of the near-wall region. This might be expected given the decrease in streamwise velocity fluctuations with normal distance evident in Figure 7 while the rms scalar fluctuations remain nearly constant in the outer portion of the near-wall region. The scalar is, of course, modeled using the streamwise velocity eigenmodes as its basis.

#### Stochastic estimation of phase error

The phase distortion induced by the scalar field produced by the dynamical model (DM) is shown in Figure 10c. Again, time for the DM is analogous to streamwise direction for the DNS. The phase error produced by the DM is seen to be strongly influenced by the presence of the streamwise vortices, with large changes as the flow jumps from one fixed point to another. Linear Stochastic Estimation (LSE) (Adrian, 1988; Adrian et al. 1989) was studied as a means to determine the phase distortion resulting from scalar fluctuations with information at only a few points. The DM results were used to test the concept for eventual application in the experiment discussed below. The DM phase error was estimated using velocity components at a few reference points. The two-point correlations used in the LSE were obtained for a long time period in the DM prediction. The LSE reference points were placed on the plane  $y^+ = x_2^+ = 17$ , near where rms fluctuations are largest; all three velocity components were used at each reference point. Figure 10 shows the phase error estimated using 2 and 4 reference points in comparison with the DM phase error. Four reference points with a spanwise spacing of  $\Delta z^+ = \Delta x_3^+ = 94$  were found to be sufficient to estimate the phase error quite accurately. The greatest spanwise distance from a reference point at which phase error is estimated corresponds approximately to the peak in the correlation between spanwise velocity and phase error; the correlation between streamwise velocity and phase error is also still significant at this spacing.

The LSE was also applied to the phase error induced by the scalar field in the direct numerical simulation (DNS) of the channel flow. The two-point correlations between velocity components and phase error were quite similar to those for the DM. However using reference point spacing close to that used above for the 4-point LSE of the DM produced a poor estimate of the DNS phase error. The reasons for this are currently under investigation. The DNS scalar field is obviously much more complex than the DM field produced by large streamwise vortices (see Figure 6 above). A few reference points along one normal plane is sufficient to estimate the DM phase error since the entire near-wall region is dominated by the streamwise vortices. The optimal placement of and minimum number of reference points required to accurately estimate the DNS phase error will be determined.

#### Round turbulent jet

In cooperation with the Air Force Phillips Laboratory, a turbulent flow facility designed to allow simultaneous measurement of flow and optical quantities was constructed (Staveley, 1994). A round turbulent jet was selected as a free shear flow with sufficient complexity to demonstrate the effects of large-scale turbulent structure upon optical propagation. The coherent structure in this flow is a ring vortex which forms within about two diameters of the nozzle exit, and develops strong circumferential variations within about 6 diameters of the nozzle exit. Hot-film anemometry is used to measure velocity in cold flow, and to measure

temperature and mass flux when the jet is heated. Laser beams are propagated across the flow transverse to the jet flow to measure beam jitter (Truman et al., 1994) or to perform tomographic reconstruction of the turbulent structure (McMackin et al., 1994).

Figure 11 shows the flow facility used to produce a vertical heated round jet and Figure 12 shows a top view of the optical bench. A lateral effect detector (or "quad cell") determines the position of a focused laser beam which has passed through the turbulent jet. The streamwise and lateral components of beam jitter (or rms fluctuation of the beam position) will be measured for different diameters of the laser beam (which essentially averages the phase error over different apertures) and for propagation through the jet at different streamwise and lateral positions. This data will be compared with computations made for a large eddy simulation of a turbulent jet obtained from Sandia National Laboratories, Livermore (Chen et al. 1993). Under a subsequent AFOSR grant, a dynamical model for a passive scalar in a round turbulent jet will be developed based on POD modes for the velocity field taken from the measurements of Glauser et al. (1993) and used to construct a dynamical model for the velocity field (Glauser et al., 1992). The LES of the jet will be used to determine relationships between the scalar field and velocity and vorticity in order to construct a dynamical model for the scalar field. These predictions will be compared with dynamic data from the jet flow facility at the Phillips Laboratory.

#### **ACKNOWLEDGEMENTS**

The assistance of Dr. Robert Moser and Dr. John Kim of the NASA-Ames Center for Turbulence Research in obtaining the numerical data for the channel flow is greatly appreciated. The assistance of Dr. Bruce Masson, Dr. John Wissler (Major, USAF) and Dr. Lenore McMackin of the Air Force Phillips Laboratory, Albuquerque, in initiating and carrying out this research is gratefully acknowledged. The assistance of Phillips Laboratory personnel and its contractors, particularly Applied Technology Associates, was essential to the construction of the turbulent round jet facility.

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## PERSONNEL

Principal Investigators: C. Randall Truman, Associate Professor  
Rick I. Zadoks, Assistant Professor

Graduate Students: Kris Larson, M.S., May 1993  
Brian Staveley, M.S., July 1994; partial support from AFOSR Summer Graduate Student Program (Phillips Laboratory)  
Hans Barsun, M.S., expected May 1995; partial support from New Mexico NASA Space Grant Fellowship  
Tim Luna, M.S., expected December 1995; partial support from UNM Southwest Hispanic Research Institute

Undergraduate Students: Dung Vo  
Brian Baltz; partial support from New Mexico NASA Space Grant Fellowship [now a graduate research assistant on Air Force-funded High Performance Computing Initiative at UNM]  
Ken Christensen; support from UNM Minority Engineering, Mathematics and Science program (funded by DOD) [applying for graduate study at Stanford, Illinois, etc.]

## **INTERACTIONS**

### **Presentations:**

- "Study of AeroOptic Effects Through the Dynamics of a Passive Scalar in Turbulent Shear Flow," University of Maryland, Mechanical Engineering, January 1994.
- "AeroOptic Effects Studied in an Axisymmetric Jet," (presented by Brian Staveley) 46th Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Albuquerque, November 1993.
- "The Effects of Turbulent Structure Dynamics on Optical Propagation Through Shear Flows," AFOSR AeroOptic Workshop, Albuquerque, August 1993 (invited).
- "The Influence of Coherent Structure on Optical Phase Distortion Through Turbulent Shear Flows," 45th Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Florida State Univ., November 1992.
- "Turbulence Structure Influence on Optical Phase Distortion," Turbulence Research: Joint AFOSR/ONR Grantee and Contractors' Meeting, Chicago, June 1992.
- "A Comparison of Optical Phase Errors Caused by Turbulent Structure in Homogeneous Shear and Channel Flow," 44th Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Arizona State University, November 1991.

### **Laboratories:**

Prof. Truman and the graduate students working at the Air Force Phillips Laboratory, Albuquerque, participate in the AeroOptics working group headed by Dr. Lenore McMackin. Dr. Bruce Masson and Dr. John Wissler (USAF Major) also participate in the group. The primary objective of this group is developing an experimental tomographic capability to study the dynamics of a turbulent shear flow. Brian Staveley designed and built the round turbulent jet facility used for his thesis research and as the model flow for the tomographic technique. Tim Luna is now examining relationships between optical jitter and temperature probe data within the jet; this will form the basis of his thesis. Dr. Wissler served as a member of Brian Staveley's thesis committee; Dr. Masson will serve in the same capacity for Tim Luna.

### **AFOSR/Phillips Laboratory Workshops**

Prof. Truman was co-organizer (with Dr. Wissler) of the June 1992 AFOSR Research Initiative Workshop on Aero-Optics in Chicago. Thirteen researchers from universities, industry and government laboratories defined the scientific questions for this topic, suggested approaches likely to yield success in answering these questions, listed expected benefits of the scientific advances, and planned ways to transition the research results to the user community. A brief report to Dr. J. McMichael was made by Prof. Truman and Dr. Wissler.

Prof. Truman participated in the August 1993 Phillips Laboratory Workshop on Image Reconstruction and Aero-Optic Metrology in Turbulence in Albuquerque. Many potential contractors and Air Force personnel made presentations and contributed to group discussions of the scientific questions relevant to this interdisciplinary topic.

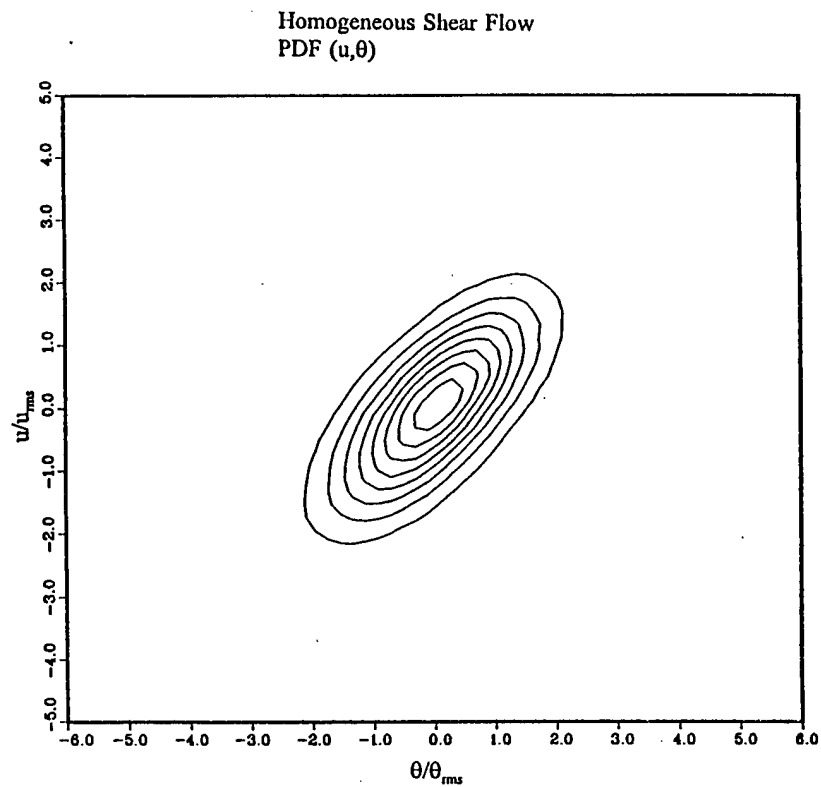


Figure 1 Joint probability density function  $\text{PDF}(u, \theta)$  for fluctuations in streamwise velocity  $u$  and passive scalar  $\theta$  in homogeneous shear flow. (DNS data from Rogers et al. (1986)).

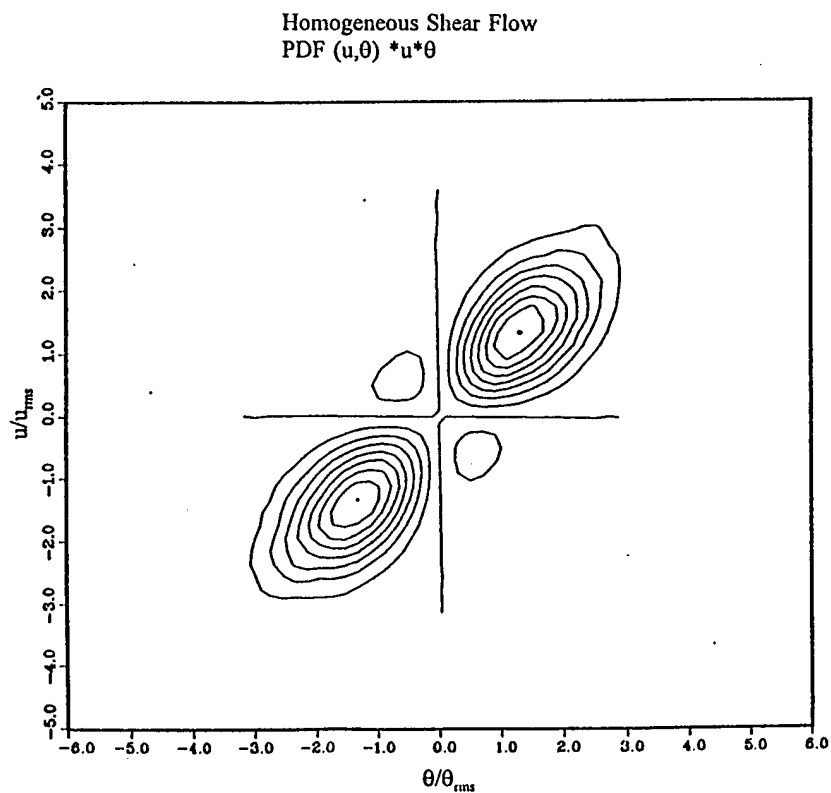


Figure 2 Product of joint probability density function  $\text{PDF}(u, \theta)$ , streamwise velocity fluctuation  $u$  and passive scalar fluctuation  $\theta$  in homogeneous shear flow. (DNS data from Rogers et al. (1986)).

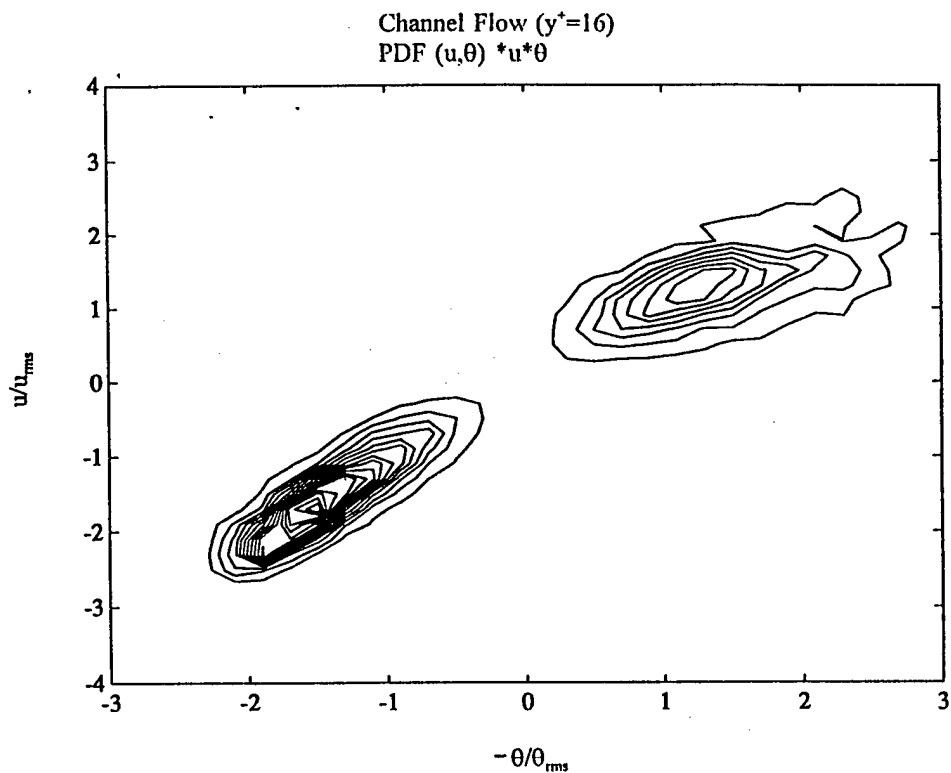


Figure 3 Product of joint probability density function PDF( $u, \theta$ ), streamwise velocity fluctuation  $u$  and passive scalar fluctuation  $\theta$  in channel flow at  $y^+ = x_2^+ = 16$ . (DNS data from Kim (1988)).

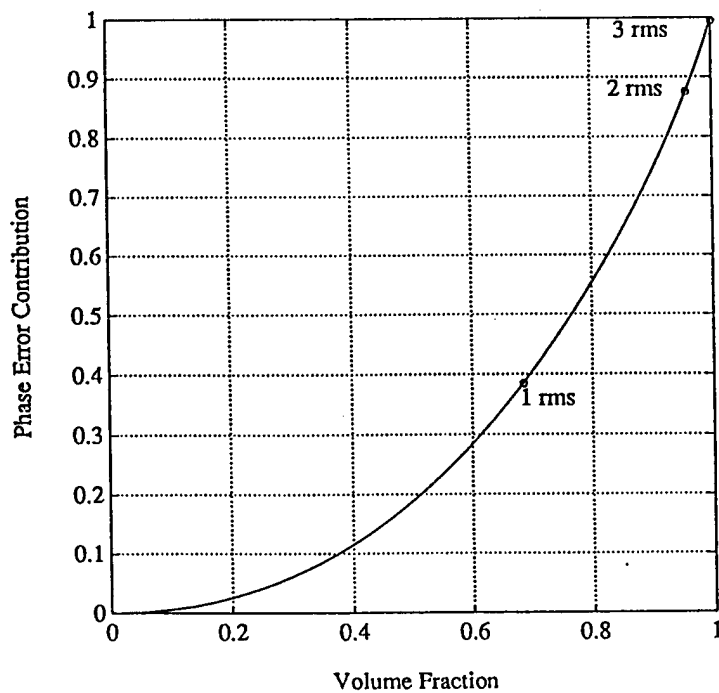


Figure 4 Contribution to phase error vs. volume fraction for scalar fluctuations in turbulent channel flow. Scalar fluctuations are normalized by  $\theta_{rms}$  for the near-wall region  $y^+ = x_2^+ \leq 40$ . (DNS data from Kim (1988)).

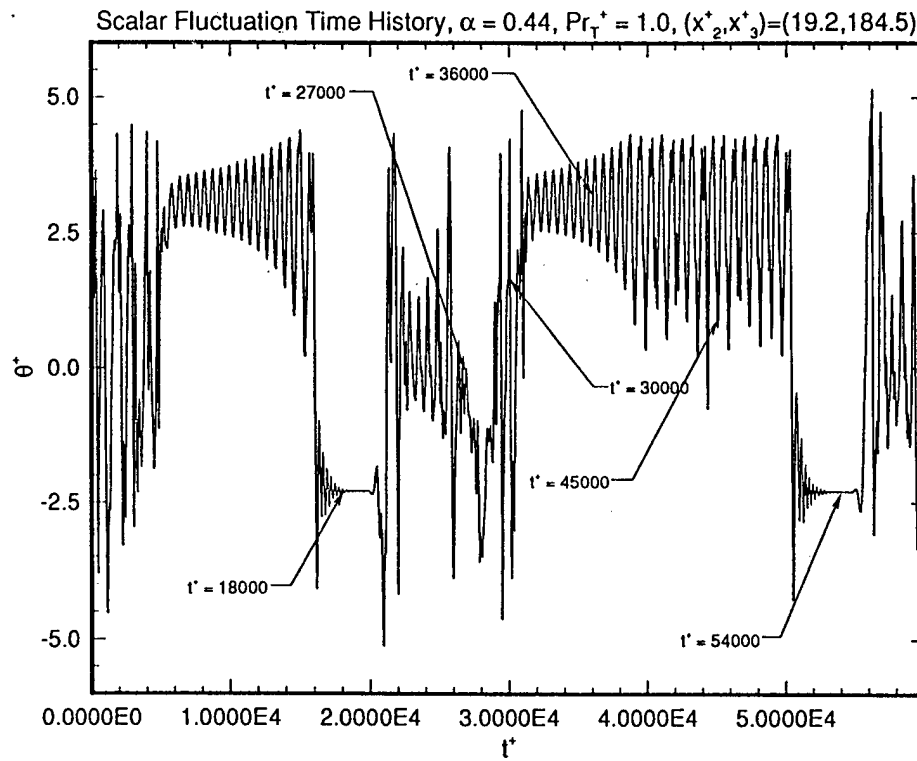


Figure 5 Time history of scalar fluctuations at  $(x_2^+, x_3^+) = (19.2, 184.5)$  noting points for which  $x_2^+ - x_3^+$  planes have been reconstructed in Figure 6.

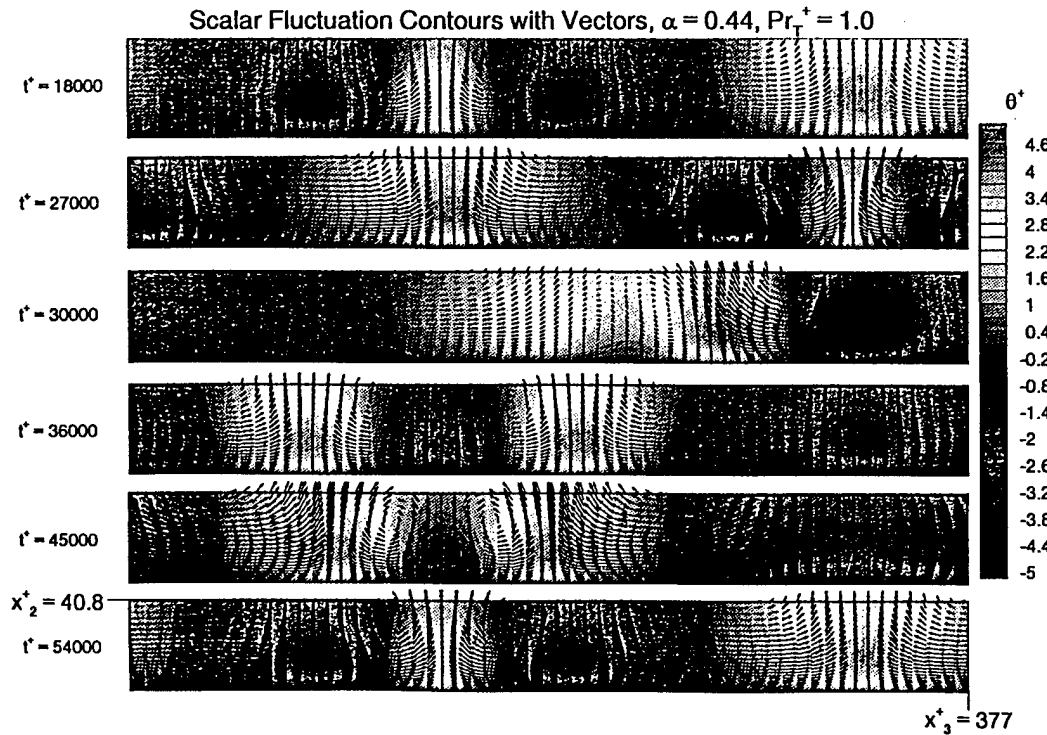


Figure 6 Reconstructed  $x_2^+ - x_3^+$  planes showing scalar fluctuation contours with cross-stream velocity fluctuation vectors for different times in the intermittent solution ( $\alpha = 0.44$ ).

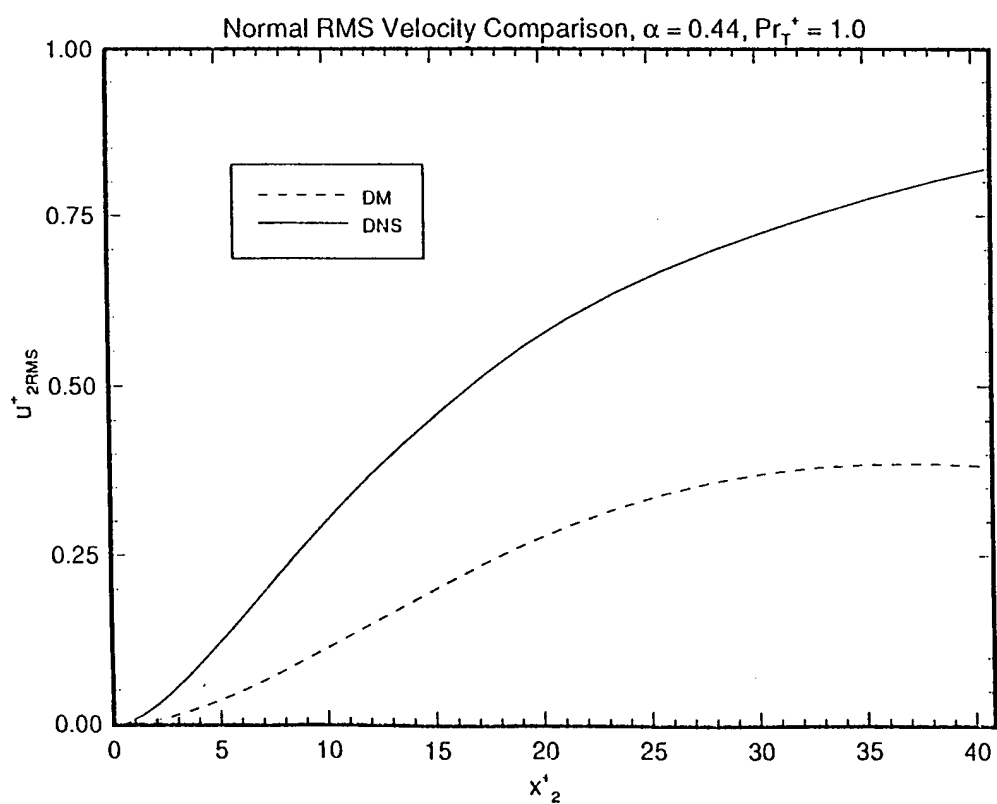
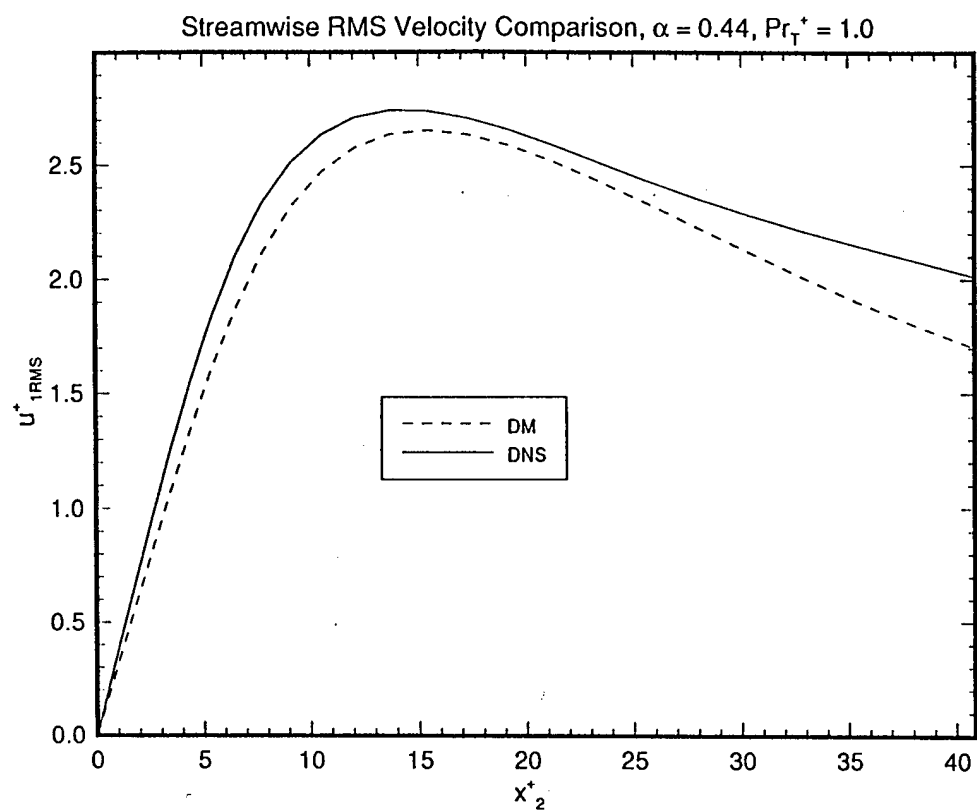


Figure 7 Normal profiles of rms fluctuations in streamwise and normal velocity components from the DM and the DNS of Moin & Moser (1989).

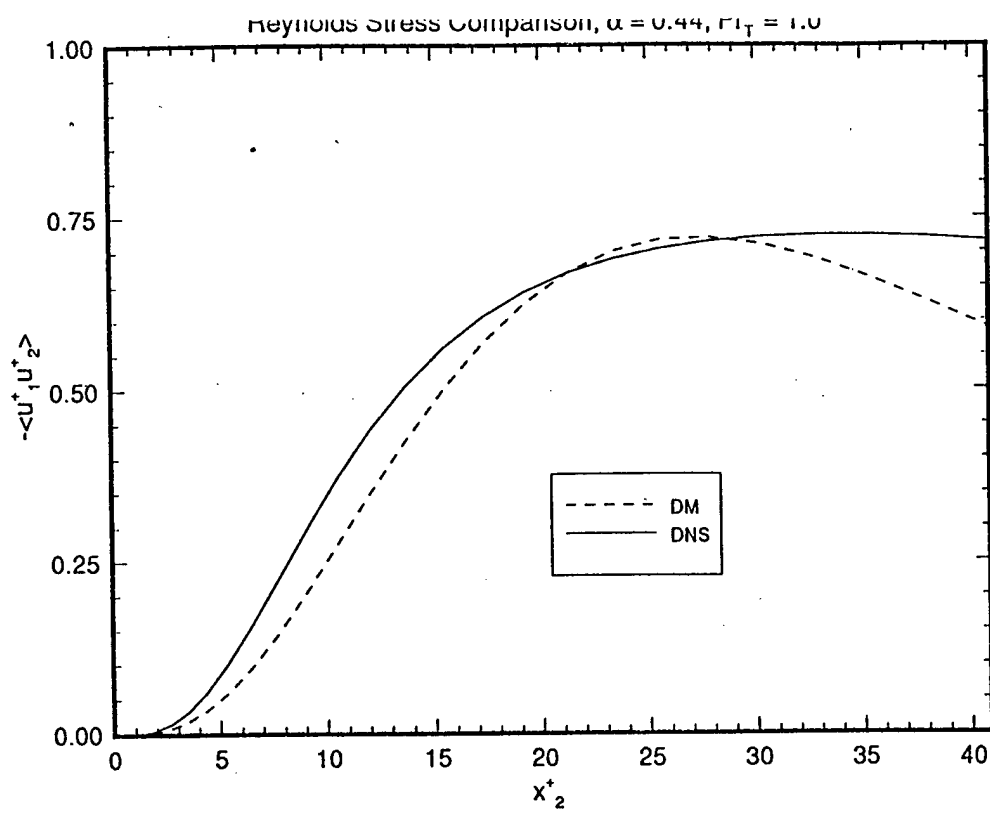


Figure 8 Normal profile of average Reynolds stress from the DM and the DNS of Moin & Moser (1989).

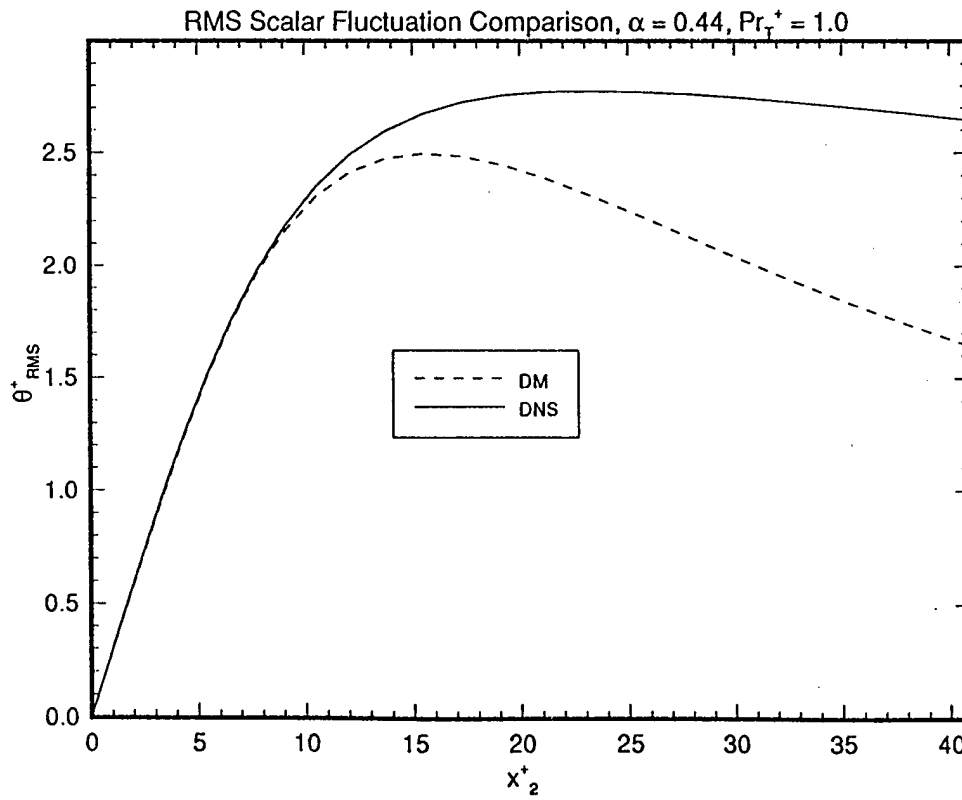
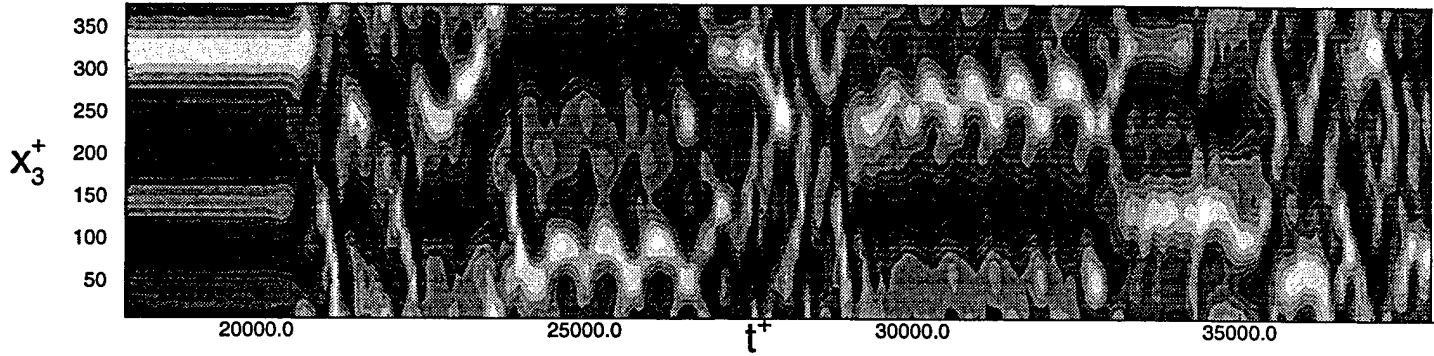
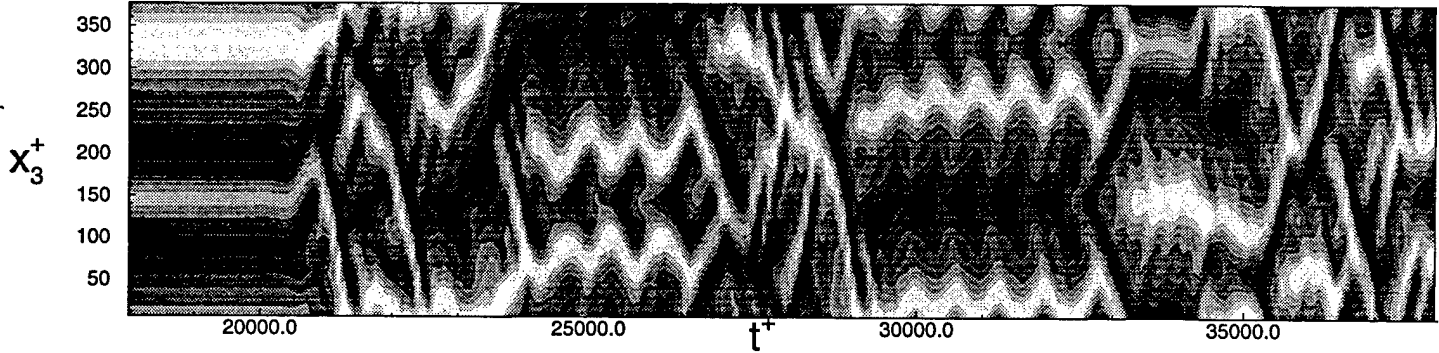


Figure 9 Normal profile of rms fluctuation in passive scalar from the DM and the DNS of Moin & Moser (1989).

### PHASE ERROR FROM 2-POINT LSE



### PHASE ERROR FROM 4-POINT LSE



### REFERENCE PHASE ERROR (from DM)

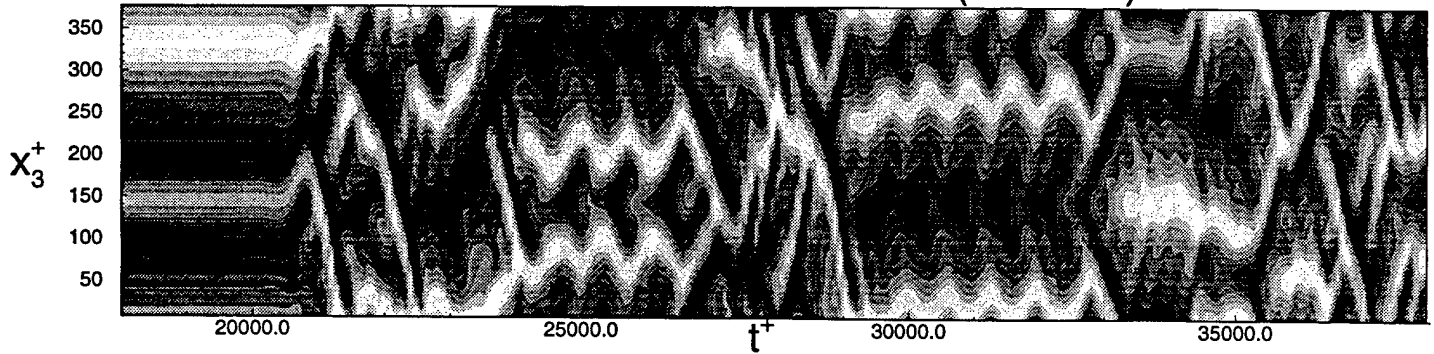


Figure 10

Optical phase error  $\Delta\phi(x_3^+, t^+)$  contours at  $x_2^+ = 40$  produced by:

- Linear Stochastic Estimate using 2 reference points on  $x_2^+ = 17$  plane;
- Linear Stochastic Estimate using 4 reference points on  $x_2^+ = 17$  plane;
- direct integration through DM scalar fluctuation field.

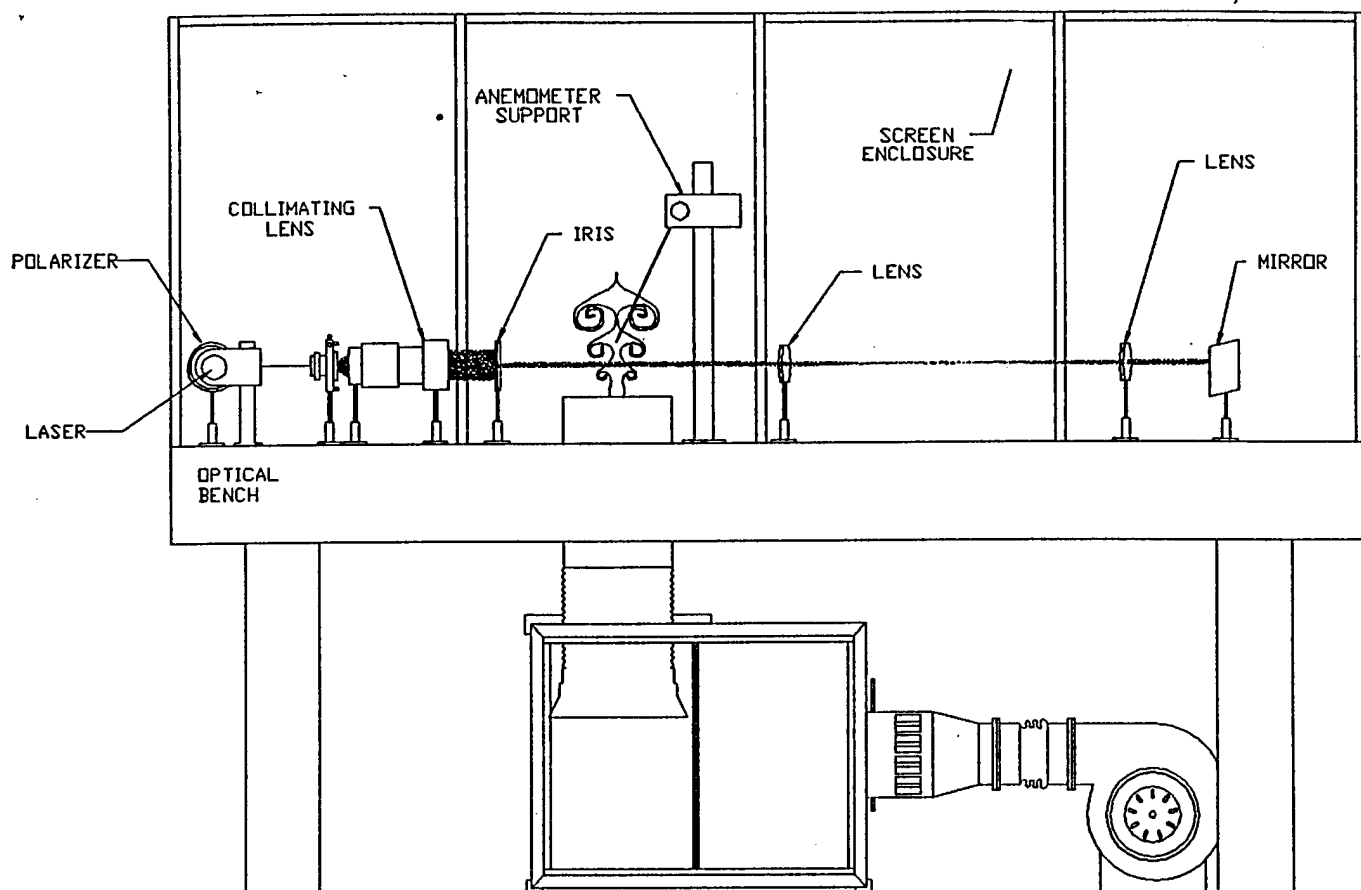


Fig. 11 Experimental apparatus for turbulent round jet, including blower, heaters and plenum below optical bench with laser beam propagation through the jet above the adjustable nozzle.

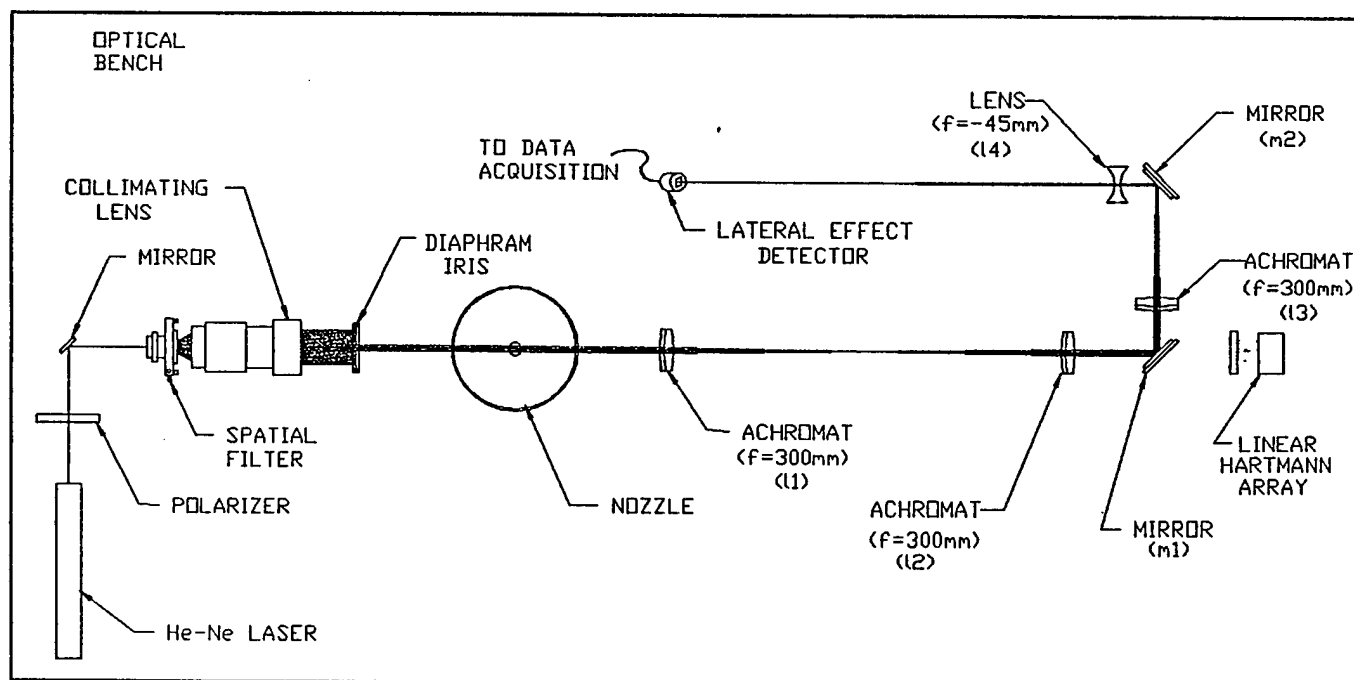


Fig. 12 Top view of optical beam path for a laser beam propagated through a turbulent round jet and then focused on a lateral effect detector to measure beam jitter.